


Linkages between sediment delivery and streambed conditions in the Lagunitas Creek watershed, Marin County, California

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Introduction

Stream channel responses to changes in sediment supply

Changes in the supply of sediment to streams can have wide-ranging effects on the form and function of fluvial ecosystems. For example, inputs of large volumes of sediment, often from landslides and bank erosion associated with rare, large storms, can result in channel aggradation, filling of pools, channel widening, and/or streambed fining (e.g., Kelsey 1980, Roberts and Church 1986, Knighton 1991, Madej 1995). Geomorphic studies in Redwood Creek, northwestern California, documented channel aggradation resulting from a massive flood event in 1964, and subsequent channel degredation and downstream transport of this sediment pulse (Janda 1978, Madej 1995, Nolan and Marron 1995). Downstream of dams, which block the transport of bedload sediment, sediment transport rates usually exceed supply and streams winnow away smaller-sized sediment, leaving behind a coarse armor layer (Williams and Wolman 1984, Ligon et al. 1995, Kondolf 1997). Because of the tremendous complexity of fluvial systems, specific stream channel responses to changes in sediment supply can vary depending on many factors such as channel form and transport processes, climate and streamflow patterns, and the distribution and type of riparian vegetation or woody debris.

Predicting the response of a stream channel to changes in sediment supply is further complicated by the fact that changes in sediment delivery are usually accompanied by changes in watershed hydrology and sediment routing. For example, land use changes (e.g., grazing, timber harvest, urbanization) often result in changes in infiltration rates and hydraulic pathways, which can cause dramatic increases in peak flows at the watershed scale (Dunne and Leopold 1978). The channelization of streams that previously were multi-channel braided systems or that ended in alluvial fans results in the loss of sediment storage and increased sediment transport to downstream reaches. Similarly, channel incision associated with human development disconnects streams from their floodplains, changing the way sediment is stored and routed through stream networks. These changes in hydrology, channel form, and connectivity are intimately connected to bed textural changes, requiring an investigation of the system in its entirety, including an understanding of historic watershed disturbances, in order to understand channel responses to land use changes.

Theoretical predictions and laboratory flume studies of stream channel responses to changes in sediment supply often focus on bed texture (grain size) responses, because factors such as channel width, slope, and hydrology are often kept constant. In response to decreasing sediment supply, Dietrich et al. (1989) observed bed armoring (coarsening) and a decrease in the size of zones of active sediment transport in their flume. Dietrich et al. (1989) proposed a dimensionless sediment transport parameter, q^*, that is the ratio of the transport rate of the surface layer to the transport rate of a layer with the grain size of the bed load (or subsurface layer). A q^* value of 1.0 indicates that the surface layer is the same size as the subsurface layer (no armoring) and that sediment supply matches the capacity of the stream to transport sediment. A q^* value of 0 suggests that sediment supply is low relative to transport capacity and that bedload transport rarely if ever occurs at bankfull flows. Similarly, Buffington and Montgomery (1999a) found that the difference between the competent (predicted) median grain size (D'_{50}) and the actual surface grain size (D_{50}) in flume studies was correlated with sediment supply: at low sediment supply the actual median grain size approached the predicted value, but at high sediment supply the streambed was much finer than predicted.

Several attempts to test these theoretical predictions in the field have been moderately successful, but have often been hampered by factors that complicate the relationship between sediment supply and bed texture. Kinerson (1990) measured q* in six California streams (including Lagunitas Creek) and found that q* was generally well correlated with sediment supply, although some streams with high sediment supply had localized armored reaches, while streams with low sediment supply were not uniformly armored. Lisle et al. (2000), studying six large gravel-bed streams in northern California and Colorado with a large (10^4) range in sediment yield, found that streams with high sediment supply had greater areas of bed mobility and coarser armor layers, as measured by q* and Shields stress (τ*). Uniform thresholds of sediment mobility were not present in sites with either high or low sediment supply, however, suggesting that local imbalances between transport capacity and grain size were responsible for the bulk of bed load transport and for driving channel evolution. Nevertheless, Lisle et al. (2000) conclude that reach-averaged bed mobility parameters can be used by watershed managers for first-order assessments of relative sediment supply and bed mobility, within the context of a sediment budget approach. Using mobility parameters as diagnostic indicators of watershed sediment dynamics, however, is complicated by the difficulty in selecting comparable study streams and by the influence of channel roughness on bed surface grain size. Working in gravel-bed streams with varying wood loading and channel bedforms (i.e., planed bed, wood-poor pool-riffle, and wood-rich pool-riffle channels), Buffington and Montgomery (1999b) found that hydraulic roughness, rather than sediment supply, was the dominant control on grain size, and that roughness elements resulted in finer streambed surfaces than was predicted from bankfull shear stress.

Most gravel-bed streams have beds that are organized into distinct textural patches of sorted particles. The overall range and number of patches in a given reach of stream have been observed to be relatively constant through time, but some patches can migrate, disappear, or expand or contract in size, while other patches appear to be stable (Dietrich et al. 2005). Patches have also been observed to form in flume studies (Dietrich et al. 1989, Lisle et al. 1993). As the supply of bed material was gradually decreased during these flume studies, inactive coarse patches expanded in size, zones of active transport narrowed, and freely moving bed load sheets disappeared, suggesting that patch dynamics may be a primary response to altered sediment supply (Dietrich et al. 2005, Nelson et al. 2009). Thus, in addition to considering the effects of sediment supply on overall changes in streambed grain size or bed mobility, attention to the number, size, and texture of patches may yield additional information about channel responses.

Changes in the texture and mobility of streambeds can have both direct and indirect effects on aquatic biota (e.g., Watters 1995). For example, multiple life stages of salmonids are intimately tied to the composition and arrangement of sediment particles on the streambed. Excess levels of fine sediment (i.e., sand and silt) in salmonid spawning gravels have a strong negative effect on egg survival in both field and laboratory studies (e.g., Everest et al. 1987). Fine sediment is also been linked to reductions in the quality of rearing habitat for salmonids, through the mechanisms of the loss of flow refugia and/or a decline in the availability of aquatic invertebrate prey (e.g., Suttle et al. 2004). Additionally, an increased frequency or depth of bed mobility can increase the risk of red scour and loss of streambed refugia during floods (e.g., Kondolf et al. 1991). Depth of bed scour is strongly influenced by surface streambed texture; small changes in the size and sorting of the streambed can greatly affect streambed mobility and embryo survival (Montgomery et al. 1996).

Lagunitas Creek

Like most streams of coastal California, and much of the Pacific coast of North America, Lagunitas Creek in Marin County, CA, has experienced large declines in populations of salmonid fishes in the 19th and 20th centuries (Brown et al. 1994). Declines in endangered coho salmon (*Oncorhynchus kisutch*) and steelhead (*O. mykiss*) populations correspond with the large-scale expansion of human land use in the Lagunitas Creek watershed including logging, agriculture, livestock grazing, urbanization, dam construction, and stream alteration. Lagunitas Creek was listed on the 303(d) list of impaired water bodies of the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) because of concerns that sediment was negatively affecting habitat for salmonids. Water bodies on the 303(d) list require the development of a total maximum daily load (TMDL), which is an action plan to improve water quality and habitat. Before developing a TMDL, it is necessary to have a strong, quantitative understanding of the effects of sediment on beneficial uses (i.e., cold-water habitat, spawning habitat, migration habitat).

Historic land use changes and management practices are believed to have had large impacts on stream channel conditions in the Lagunitas Creek watershed as a result of changes in the supply and transport of sediment. For example, large portions of the channel network in aggradational environments have undergone channel incision, transforming complex, multi-channel fluvial ecosystems into simple, single-thread channels that are disconnected from their historic floodplains. This pervasive process of incision is likely a result of a combination of factors including reductions in wood loading to channels, direct modification of channels including the removal of wood, changes in watershed hydrology associated with timber harvest and agriculture, and ubiquitous changes in grassland composition and soil compaction from grazing and agriculture. Currently, sediment input is believed to be elevated by a factor of 2 - 10 times over natural levels across much of the watershed (Stillwater Sciences 2010), although dams block a large amount of coarse sediment from entering the mainstem of Lagunitas Creek. Despite the reduced supply of sediment below the dams, the delivery of large amounts of fine sediment from tributaries combined with a lack of flushing flows appear to be important controls on bed conditions in Lagunitas Creek, which have fined in recent years (Hecht et al. 2008). Given this complex history of altered geomorphic processes, how are streams in the Lagunitas Creek watershed currently functioning, and what is the current effect of sediment input on channel form and bed texture?

The conceptual approach of this study is based upon the idea that changes in land use practices affect sediment supply to stream channels (e.g., Montgomery et al. 2000), which interact with patterns of streamflow to cause changes in channel form and streambed texture, which in turn affects the quality of habitat for salmonids (e.g., Cover et al. 2008). The objective of this report is to examine the relationships among sediment supply and stream channel characteristics among sub-basins in the Lagunitas Creek watershed to determine if elevated sediment supply has resulted in changes in streambed characteristics that are relevant to salmonid habitat. I measured a variety of streambed characteristics, including fine sediment, patchiness, and mobility parameters (such as q^* and τ^*,), in seven tributary streams with a range of sediment supply in order to (1) characterize the responses of channels to changes in sediment supply and to (2) identify metrics that can be used in future monitoring efforts to assess sediment supply and channel responses.

Methods

Study sites

Study sites were located in six tributary streams with basin areas between ~2 and 4 km^2, and one larger tributary stream (Lower Nicasio Creek) located downstream of a dam (Table 1). Several of the small streams are also affected by dams; two of the sites (Upper Nicasio and Devil's Gulch) have portions of their streamflow and sediment delivery regulated by small dams, while a third stream (Cheda Creek) has a historic dam that is believed to no longer be functional due to infilling by sediment. Sediment supply and hydrology in a fourth small basin (Larsen Creek) is affected by a constructed pond and artificial drainage system through a golf course. Every tributary stream to the mainstem of Lagunitas Creek or San Geronimo Creek with a basin area larger than 2 km^2 was included in this study, except one that was inaccessible because of private property issues.

I established reaches that were 9-10 bankfull channel widths long in each study stream (except in Lower Nicasio Creek where the reach was ~4 bankfull channel widths long) (Table 1). Within constraints of access to private property, reaches were located in order to minimize flow obstructions from large wood, banks, bars, and other obstacles. However, streams exhibited considerable variability with regards to sinuosity and flow obstructions (Table 1). Most study streams are confined in narrow valleys, although two streams (Larsen and Woodacre) flow through a wide alluvial valley (San Geronimo Valley) (Table 1). All sites have undergone historic or recent channel incision, however, resulting in high entrenchment (small or non-existent active floodplains) (Table 1). Additional reach and basin information, including all raw data, is presented in the appendix to this report.

Sediment delivery estimates

Sediment delivery to study reaches was estimated using (1) a quantitative sediment budget based on geomorphic terranes (Stillwater Sciences 2010), and (2) a four category (very low, low, medium, high) qualitative assessment based on watershed surveys and knowledge of local geology, dams, and land use (Table 2). The quantitative sediment budget was developed by Stillwater Sciences (2010) and was based on sediment sources determined from a time series of aerial photographs, existing sediment source inventories, and limited hillslope and in-channel field surveys. Sediment production was extrapolated across the watershed through the use of Geomorphic Landscape Units (GLU's), whereby the watershed was stratified into areas of similar geology, land cover, and slope. Sediment production from roads and trails was assessed using a digital terrain-based empirical model (SEDMODL2) applied to a comprehensive survey of road and trail types within the watershed. Sediment production estimates for individual basins should be used with some caution because production from known sediment source areas was extrapolated based on GLU's, and forested areas were underrepresented in air photo and field surveys. However, basin-wide estimates of sediment production are in good agreement with sediment yield measurements from gaging stations, reservoir bathymetry studies, and studies from nearby watersheds.

Table 1. Basin and Channel Characteristics of Study Reaches

	Lower Nicasio	Larsen	Upper Nicasio	Devil's Gulch	Arroyo	Cheda	Woodacre
Basin Area- Total (km2)	95.3	1.7	2.6	4.0	3.5	3.0	3.7
Basin Area- Unregulated (km2)	2.0	0.7	1.6	3.8	3.5	3.0	3.7
Channel Slope (m/m)	0.0063	0.0080	0.0166	0.0110	0.0103	0.0140	0.0130
Stream Power (km^2)[1]	0.600	0.014	0.043	0.044	0.036	0.042	0.048
Reach Length (m)	45	45	46	60	34	50	53
Reach Length (Bankfull Widths)	3.8	10.0	9.2	10.0	8.7	8.7	9.6
Sinuosity	1.03	1.45	1.17	1.13	1.08	1.17	1.52
Number of Large Wood Pieces	1	3	2	3	0	2	0
BF Width (m)	11.9	4.5	5.0	6.0	3.9	5.8	5.5
BF Depth (m)	0.89	0.29	0.33	0.49	0.42	0.41	0.45
Confinement[2]	Med	Low	Med	High	Med	Med	Low
Entrenchment[3]	High	High	High	High	High	High	High

Textural patches and streambed mapping

In each study reach I visually identified and mapped distinct textural patches on the streambed using a system based on the classification scheme of Buffington and Montgomery (1999c). I utilized the unary, 15 category Level I + II scheme (as recommended by Buffington and Montgomery (1999c) for most field applications), with several minor modifications. Level I of the classification scheme categorizes textural patches based on the relative abundance of the major size classes: sand (S), gravel (G), cobble (C), and boulder (B). Major size classes making up >10% (modified from >5% in the Montgomery and Buffington (1999b) system) of the textural patch were included in the facies name, with the dominant size class being designated with a capital letter. All of the patches I encountered in the study sites plotted in the sand-gravel-cobble ternary (Figure 1). Level II of the classification further describes the size range of the major size class that was most common. I simplified the 5 standard gravel sub-categories into 3 sub-categories to simplify the classification system and improve the accuracy of the visual classification (Table 3). The smallest size classes of gravel were grouped into a 2 phi category (i.e., 2-8 mm), while the larger size classes were grouped into 1.5 phi categories (i.e., 8-22.6 mm and 22.6-64 mm). For details of the naming conventions, please see Buffington and Montgomery (1999c).

Textural patches were delimited by placing pins and stakes around the approximate boundaries of patches. Patches were mapped by measuring the lateral distance of patch boundaries relative to a tape stretched along the center of the channel. In addition to patch

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[1] Stream power is defined as the product of slope and total drainage area.
[2] Confinement is a relative measure of the ratio of the bankfull channel width to the valley width; it reflects the degree to which the channel has the potential for lateral movement across a valley.
[3] Entrenchment is a relative measure of the ratio of the bankfull width to the flood-prone width (width at 2x bankfull depth); it reflects the degree to which bankfull or larger floods spill out on to a floodplain. All of the study streams are highly entrenched because they are disconnected from their historic floodplains.

boundaries, I also measured and mapped the locations of large wood pieces, the wetted area of the channel, and the edges of the bankfull channel.

Table 2. Sediment production in the study basins

Stream	**Unregulated Basin Area (km^2)**	**Total Basin Area (km^2)**	**Sediment Production-Sediment Budget ($t\ km^{-2}\ y^{-1}$)[4]**	**Sediment Supply-Qualitative**	**Notes on Geology, Dams, and Land Use**
Lower Nicasio	95.3	2.0	0.1	Very Low	Downstream of Seeger Dam, a 35 m high dam constructed in 1961 by MMWD. Stream was channelized as a result of construction and re-alignment of Pt. Reyes-Petaluma Rd.
Larsen	0.7	1.7	162	Low	Mélange and Quaternary alluvium; over half of basin drains into managed pond system and culverts under golf course
Upper Nicasio	1.6	2.6	175	Low	Steep headwaters drain to dammed pond; portions of unregulated basin is disconnected by roadways
Devil's Gulch	3.8	4.0	288	Medium	Resistant greenstone and metamorphic rocks with some mélange; small dam in headwaters; mostly protected parkland
Arroyo	3.5	3.5	363	Medium	Mostly resistant greenstone (Mt. Barnaby) with some Franciscan mélange; residential land use and roads
Cheda	3.0	3.0	368	High	Franciscan mélange with some resistant greenstone; dirt roads and cattle grazing
Woodacre	3.7	3.7	374	High	Most highly developed sub-basin; extensive paved and unpaved road network on steep hillslopes

[4] Sediment production estimates were determined from Stillwater Sciences (2010). Modifications were made for basins with dams (Devil's Gulch, Larsen, lower Nicasio, and upper Nicasio) by assuming that (1) sediment production was the same in regulated and unregulated portions of the basin, and (2) dams were 100% effective at stopping sediment supply.

Table 3. Grain Size Divisions and Names Used in this Study

Name	Abbreviation	ϕ	Size (mm)
Boulder	B	-8 to -6	256 - 2048
Cobble	C	-6 to -8	64 - 256
Gravel			
Large[5]	G_L	-4.5 to -6	22.6 – 64
Medium	Gm	-3 to -4.5	8 – 22.6
Fine	G_f	-1 to -3	2 – 8
Sand	S	4 to -1	0.0625 - 2

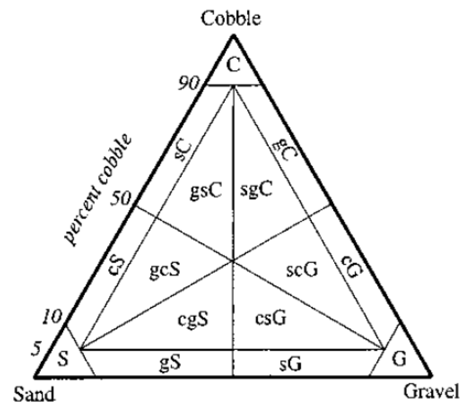

Figure 1: Ternary diagram of patch types composed of sand, gravel, and cobble substrate types, after Buffington and Montgomery (1999c). A major substrate type is included in the name of a patch if it comprises more than 10% of the patch (by area). The dominant substrate type is listed last, and is a capital letter.

Surface particle size

Surface particle size distributions for each textural patch were determined from transect-based pebble counts of a minimum of 50 (small patches 0.5-5 m^2) or 100 (large patches >5 m^2) particles, with grains <2 mm grouped into a single category. Total numbers of grains sampled per reach varied from ~200 to >1000, depending upon the number of textural patches. Cobble embeddedness was determined for every cobble-sized stone (>64 mm) encountered during pebble counts.

Bed surface fine sediment was measured and calculated in several ways: (1) the proportion of the streambed covered in sand-dominant patches (i.e., S, gS), (2) the proportion of the streambed covered in sand or fine gravel dominant patches (i.e., S, gS, sGf, Gf), (3) the proportion of the streambed covered by sand, based on spatially-weighted patch-based pebble counts, and (4) average cobble embeddedness (the average proportion of cobble-sized stones buried by sand and fine gravel). Similarly, several variations of reach-average bed surface median grain size were calculated, depending upon whether fine sediment was included: (1) D_{50} is the median grain size including all sand, (2) D_{50p} is the median grain size excluding patches of sand and fine gravel (i.e., S, gS, sGf, Gf), and (3) D_{50s} is the median grain size excluding all sand.

[5] 'Large' was used in place of 'coarse' to avoid confusion between 'cobble' and 'coarse', which would both be abbreviated by the letter 'c'.

Subsurface particle size

Bulk samples of subsurface material were taken subaerially (bars, exposed margins) or in shallow water (< 10 cm) where velocities were insufficient to transport bed material >1 mm during sampling. Sampling locations were generally chosen within planar bed features that represented the dominant surface textural patches. The surface layer of the streambed was removed by hand to a depth of the longest diameter of the largest surface particle; subsurface material was then sampled with a shovel to a depth of 20-25 cm. At three of the sites (Cheda, Larsen, Lower Nicasio), >100 kg of subsurface material was sampled from each of 2-3 ~0.5 m^2 locations, resulting in 250-350 kg of total bed material. Subsurface material was wet-sieved in the field with the following sieve sizes: 32 mm, 16 mm, 8 mm, 4 mm, 2 mm, and 1 mm. Once sieved, particles were dried on tarps and then weighed using a 35 kg scale (precision, 0.2 kg). At the other four sites (Arroyo, Devil's Gulch, Lower Nicasio, Woodacre), due to time and access constraints, a total of 40 – 85 kg of subsurface material was removed from 2-3 ~0.25 m^2 locations. The coarsest portion of the sample was separated with a 32 mm sieve and weighed, while the <32 mm portion of the sampled was wet sieved in the laboratory. Even with the smaller sample volumes, the largest stone in the sample comprised <2% of the total sample weight, well below a criterion of 5% recommended by Church et al. (1987). For the purposes of calculating the median subsurface grain size (D_{s50s}) for bed mobility calculations, sand (1-2 mm) was excluded from grain size distributions.

Topographic surveys

In each study reach I performed topographic surveys using a tape and stadia rod and either an autolevel or laser level. Longitudinal surveys included points along the thalweg, tops of bars, and bankfull stage. Additionally, 1-3 cross-section surveys were surveyed per reach, depending on the complexity of the channel. Channel slope was determined from bankfull indicators included in the long profile survey; when bankfull indicators were uncommon or poorly resolved, the slope of the thalweg between multiple riffle crests was used to corroborate bankfull indicators. Average bankfull depth and bankfull width was determined from cross-section surveys.

Bed mobility parameters

I calculated several indicators of streambed mobility using data on surface and subsurface grain sizes, bankfull depth, and slope. Increased channel roughness, caused for example by large wood, bedrock outcrops, or channel bends and meanders, causes decreased shear stress acting on the streambed and changes in sediment transport and surface grain size (Buffington and Montgomery 1999c).

Shields stress (τ^*) is a nondimensional measure of bed mobility. I calculated Shields stress at bankfull flow as:

$$\tau^* = \tau_b / ((\rho_s - \rho)\, g\, D_{50p})$$

where τ_b is shear stress, calculated from bankfull reach-average values ($\tau_b = \rho g H S$; where ρ is the density of water, g is gravitational acceleration, H is bankfull depth, and S is slope),

p_s is the density of sediment, and D_{50p} is the bed surface median grain size (excluding sand and fine gravel patches). Sand and fine gravel patches were excluded from the Shields stress calculation, but interstitial sand within coarser gravel and cobble patches were included in the determination of median grain size because sand can increase mobility and transport rates of coarser particles (e.g., Wilcock 1998). In general, streambeds with τ* values < 0.03 are considered immobile, values 0.03 - 0.06 are considered partially mobile, and values > 0.06 indicate full bed mobility (Lisle et al. 2000).

Q* (a capital letter is used to denote a value calculated from reach-averaged parameters) is the ratio of predicted bed load transport for the bed surface (from the surface median grain size) to that based on the particle size of the load (from the subsurface median grain size) (Dietrich et al. 1989). As the streambed becomes armored (coarser than the subsurface), as predicted with low sediment supply rates, the bed load transport rates predicted from the surface median grain size becomes less than rates predicted from the finer subsurface. Thus, a Q* value of 0 indicates no bed mobility, while a Q* value of 1.0 indicates that no armoring exists and increases in sediment supply must be accommodated by bed aggradation. Particle sizes <2 mm were excluded from both surface and subsurface grain-size distributions for Q* calculations in order to remove particles that would be suspended at bankfull stage. Following Dietrich et al. (1989), Q* was calculated as:

$$Q^* = ((\tau_b - \tau_c) / (\tau_b - \tau_{cls}))^{\wedge 1.5}$$

where τ_b is reach-averaged shear stress (pgHS), τ_{cs} is the critical shear stress to move the median grain size (excluding sand) of the bed surface, and T_{cls} is the critical shear stress to move the median grain size (excluding sand) of the subsurface, or load.

I also calculated the difference between the competent median grain size on the bed surface and the observed median grain size on the bed surface ($D'_{50} - D_{50}$) after Buffington and Montgomery (1999a), which is hypothesized to be a function of sediment supply rate in equilibrium channels.

Data analysis

The primary objective of this study was to examine the relationships among sediment supply and three broad categories of streambed characteristics: (1) textural patchiness, (2) fine sediment, and (3) bed mobility. In order to examine these relationships, I plotted the various streambed characteristics (dependent variables) versus both the quantitative (sediment budget modeling) and qualitative (professional judgment) sediment supply predictions (independent variables). Because of the low number of study sites (n = 7), and the potential for not meeting assumptions of normality of data, I assessed the strength of statistical relationships by using a non-parametric measure of statistical dependence between two variables, Spearman's rank correlation coefficient (ρ). A high Spearman rank coefficient (close to 1.0) indicates that Y tends to increase when X increases. Likewise, a value near -1.0 indicates a strong negative relationship. A Spearman coefficient of 0 indicates that there is no tendency for Y to increase or decrease when X increases. The Spearman rank correlation coefficient does not require linear functions between variables; it examines the relationship between two variables for any monotonic function. I also considered channel sinuosity as a dependent variable for examining relationships with measures of textural patchiness and fine sediment because sinuosity (frequency and sharpness of bends) is one of the largest contributors to hydraulic roughness in these study streams, which could have large effects on streambed textural characteristics (Buffington and Montgomery 1999b). The interpretation of a correlation coefficient depends upon context; for the purposes of this study, I used an arbitrary criteria of ±0.8 for identifying strong correlation between variables.

Results

Patches

The results of the field survey indicate that streambed patchiness was strongly correlated with the qualitative assessment of sediment supply (ρ = 0.89) (Table 4; Figure 2B). Sites hypothesized to have the highest sediment supply (Cheda and Woodacre) had >12 discrete textural patches, while sites with low or medium sediment supply had <10. The site with very low sediment supply (LN) contained only one homogenous patch. The number of patches present was less strongly correlated with the quantitative measure of sediment supply (ρ = 0.75) and channel sinuosity (ρ = 0.63) (Figures 2A, 2C; Table 4).

Fine sediment

The proportion of the streambed covered in fine sediment (< 2mm) was not well correlated with quantitative (ρ = 0.50) or qualitative (ρ = 0.39) predictions of sediment production or sinuosity (ρ = 0.37) (Figure 3, Table 4). However, the two sites with the highest channel sinuosity had more sand than 4 out of 5 of the lower sinuosity sites (Figure 3C). Sites hypothesized to have the highest sediment supply had variable levels of sand on the streambed (11-29%). The site with the lowest sediment supply and lowest sinuosity (LN) had the least fine sediment.

The proportion of the streambed covered in sand-dominant patches was not well correlated with sediment supply, but was strongly correlated with sinuosity (ρ = 0.88) (Figure 4, Table 4). Sites with low sinuosity had uniformly low proportions of the bed covered by sand patches (<5%), and the two sites with higher sinuosity (Larsen, Woodacre) had a greater extent of sand patches (13% and 36%, respectively) (Figure 4C). The site with the highest proportion of sand patches (Woodacre) had the highest predicted sediment delivery among the study sites (Figure 4A).

Similarly, the extent of sand and fine gravel patches was not well correlated with sediment supply, but was strongly correlated with sinuosity (ρ = 0.88) (Table 4). Sites with high sinuosity had high proportions of the bed covered by sand and fine gravel patches (Figure 5C).

Average cobble embeddedness, unlike other measures of fine sediment, was positively correlated with both quantitative (ρ = 0.88) and qualitative (ρ = 0.80) measures of sediment supply, and uncorrelated with sinuosity (Figure 6, Table 4). However, there was relatively little overall variation in average embeddedness among most of the sites; with the exception of Lower Nicasio (13%) and Larsen Creek (23%), the other five sites ranged in average embeddedness from 28% to 32% (Figure 6).

Bed mobility

Shields stress (τ^*) was strongly correlated with quantitative predictions of spatially averaged sediment production (ρ = 0.88) and the qualitative sediment supply predictions (ρ = 0.89), but poorly correlated with sinuosity (ρ = 0.63) (Table 4). Streams hypothesized to have low and medium sediment supply had consistently lower Shields numbers (0.08-0.10), while the two sites hypothesized to have high sediment supply (Cheda and Woodacre) had high Shields values (0.16 and 0.18, respectively) (Figures 7A, 7B).

Reach-averaged Q* was moderately correlated with quantitative (ρ = 0.67) and qualitative (ρ = 0.72) measures of sediment supply (Table 4). Reaches hypothesized to have low and medium sediment supply had lower Q* values (< 0.67) than reaches with high sediment supply (Q* > 1.0) (Figures 8A, 8B).

The reach-averaged difference between predicted D_{50} and actual D_{50} ($D'_{50} – D_{50}$) was very well correlated with both the quantitative (ρ = 0.96) and qualitative (ρ = 0.93) estimates of sediment production (Table 4). Over-prediction of D_{50} was substantially greater at sites with high predicted sediment supply (57, 71 mm) than at sites with medium or low sediment supply (range, 17-36 mm) (Figures 9A, 9B).

Table 4. Spearman rank correlation coefficients (ρ) among sediment supply/sinuosity measures (independent variables) and streambed characteristics (dependent variables). Values >0.8 are shown in bold.

Streambed Characteristics	Quantitative Sediment Supply (tonnes yr^{-1} km^{-2})	Qualitative Sediment Supply (Low/Med/High)	Sinuosity
Patchiness			
Number of Patches	0.75	**0.89**	0.63
Fine Sediment			
Surface Sand, reach-wide	0.50	0.39	0.37
Surface Sand Patches	0.54	0.55	**0.88**
Surface S or Gf Patches	0.54	0.55	**0.88**
Avg. Cobble Embeddedness (%)	**0.88**	**0.80**	0.46
Bed Mobility and Transport			
τ* Shields stress	**0.88**	**0.89**	0.63
Q*	0.67	0.72	0.75
Predicted - Actual D50 (mm)	**0.96**	**0.93**	0.54

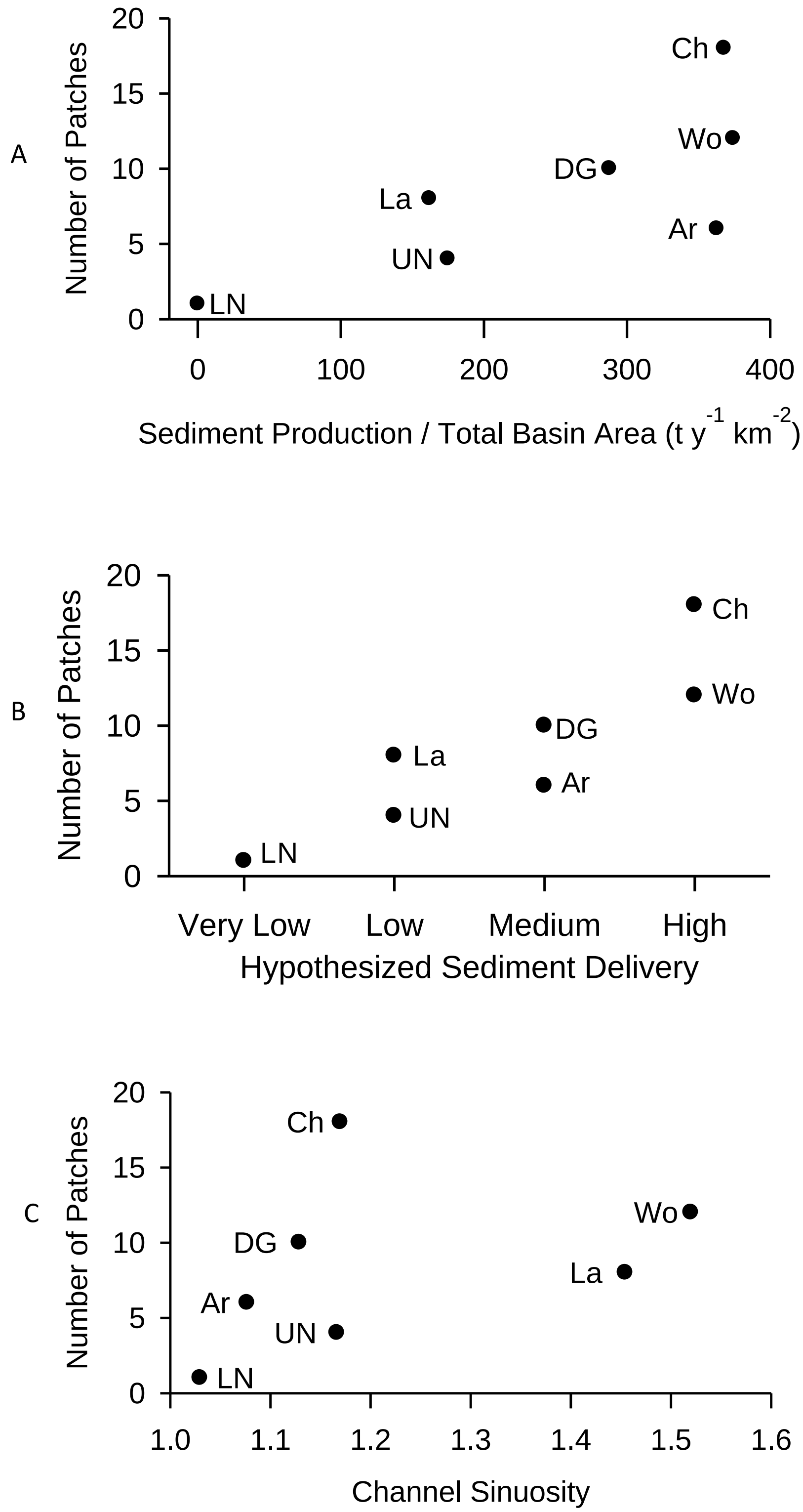

Figure 2. The number of patches versus a quantitative estimate of sediment production (A), a qualitative assessment of sediment delivery (B), and channel sinuosity (C).

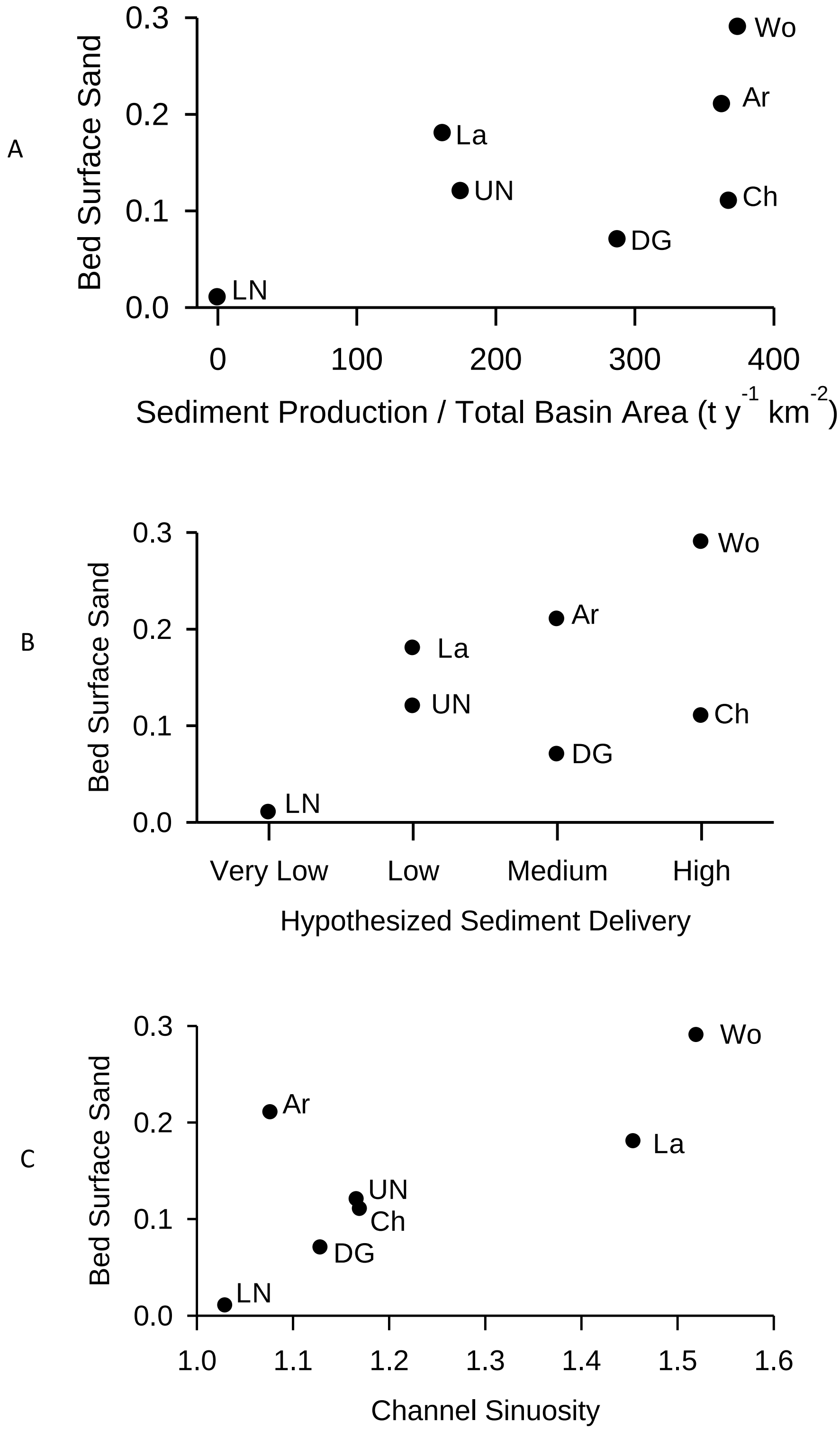

Figure 3. The proportion of the bed covered by sand (2mm) versus a quantitative estimate of sediment production (A), a qualitative assessment of sediment delivery (B), and channel sinuosity (C).

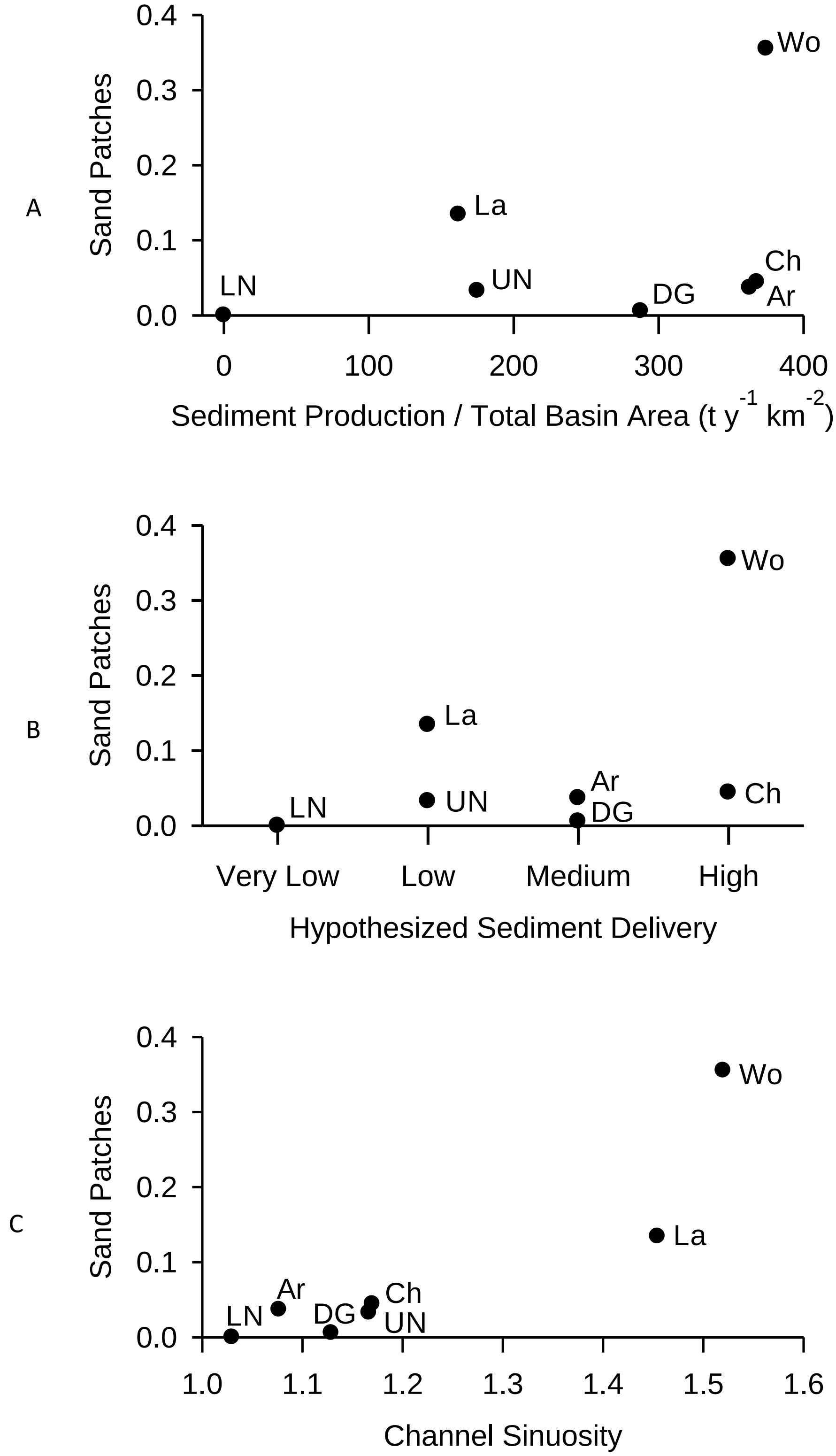

Figure 4. The proportion of the bed covered by sand-dominant patches versus a quantitative estimate of sediment production (A), a qualitative assessment of sediment delivery (B), and channel sinuosity (C).

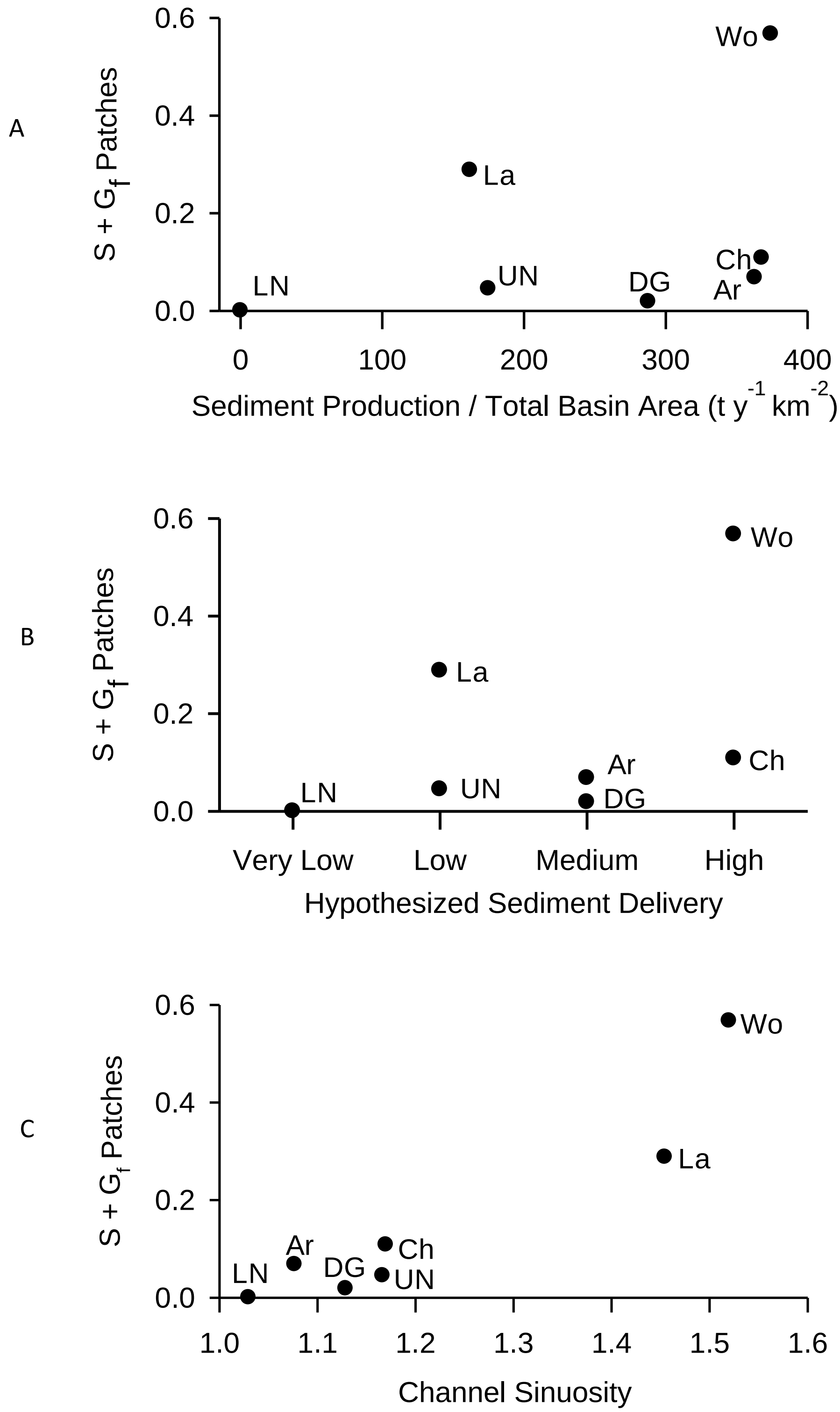

Figure 5. The proportion of the bed covered by sand or fine gravel dominant patches versus a quantitative estimate of sediment production (A), a qualitative assessment of sediment delivery (B), and channel sinuosity (C).

A

B

C

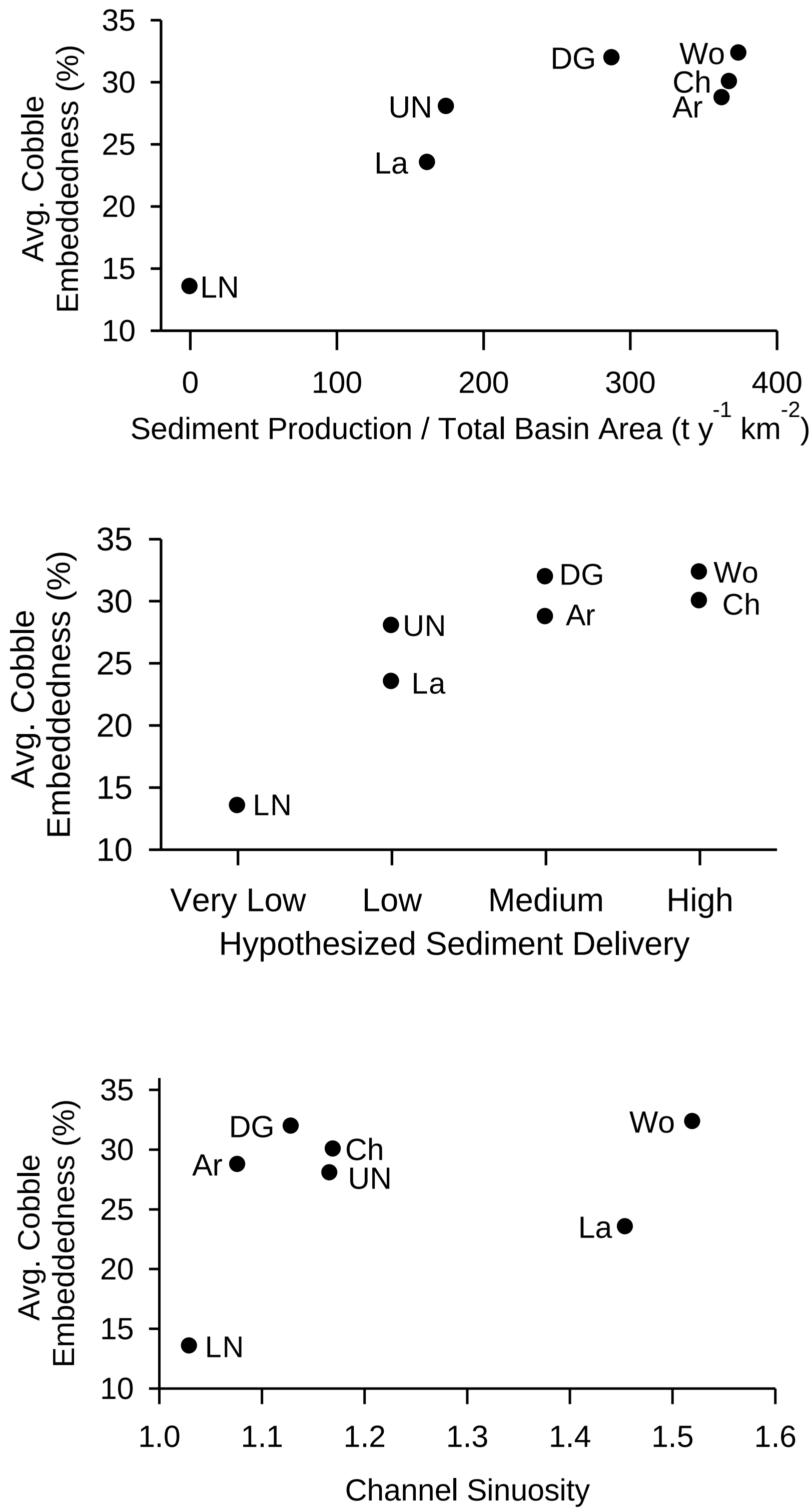

Figure 6. Average cobble embeddedness versus a quantitative estimate of sediment production (A), a qualitative assessment of sediment delivery (B), and channel sinuosity (C)

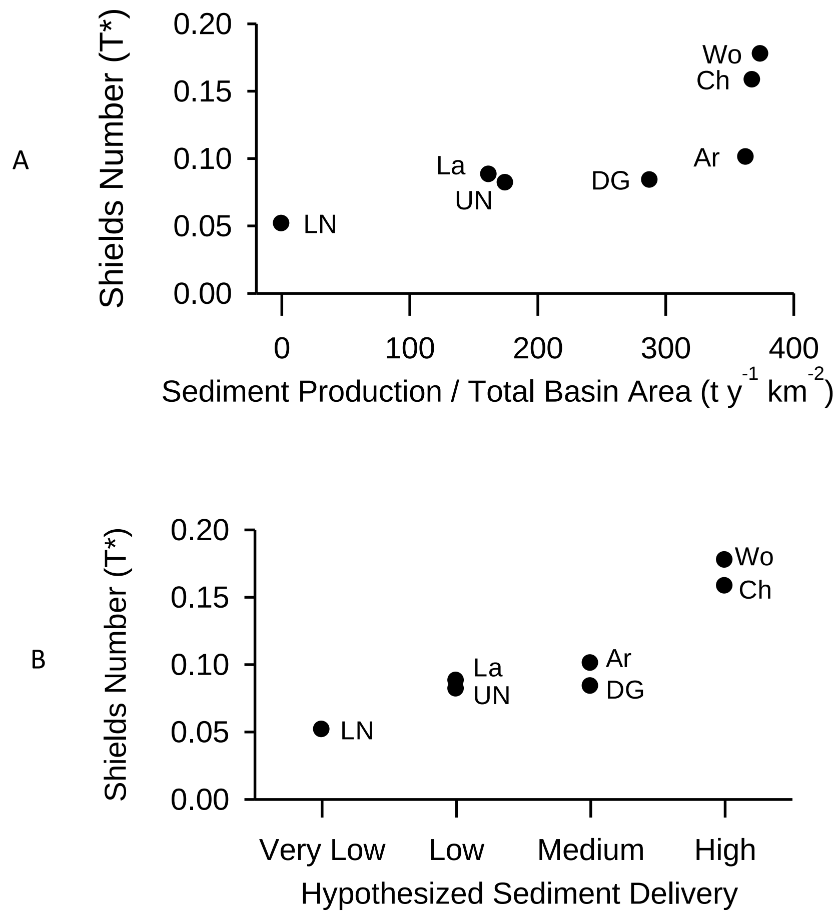

Figure 7. Reach-average Shields stress (τ*) versus a quantitative estimate of sediment production (A) and a qualitative assessment of sediment delivery (B).

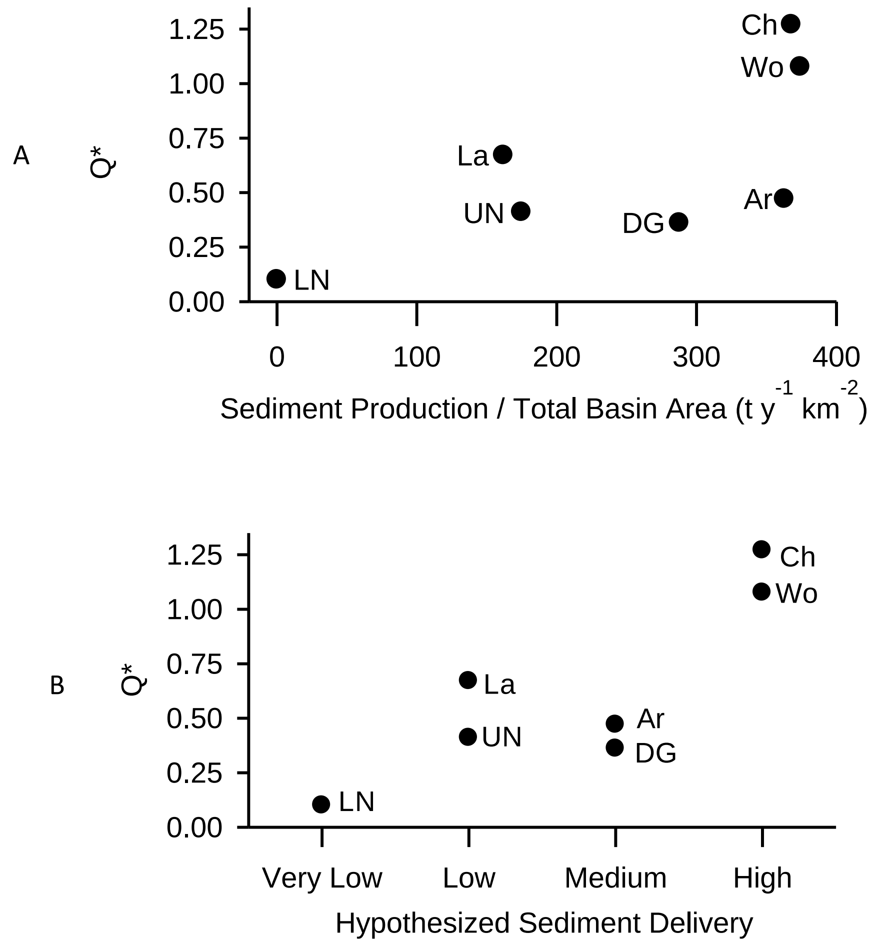

Figure 8. Reach-average Q* versus a quantitative estimate of sediment production (A) and a qualitative assessment of sediment delivery (B).

A

B

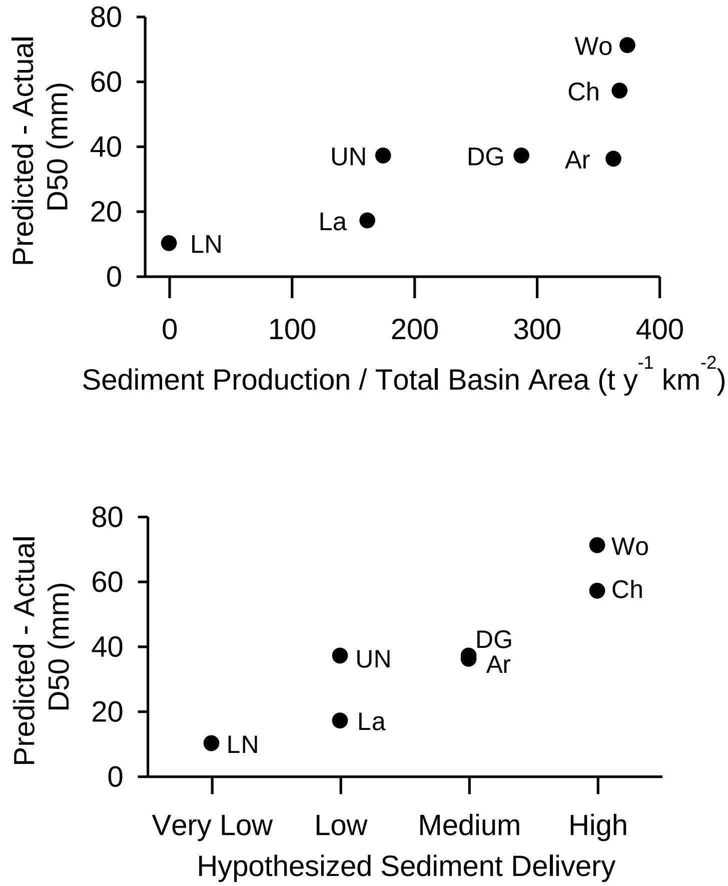

Figure 9. Reach-average differences between predicted and actual D_{50} versus a quantitative estimate of sediment production (A) and a qualitative assessment of sediment delivery (B).

Discussion

Relationships between sediment supply and streambed characteristics

Empirical studies from throughout the world, and especially in the Pacific Coastal Ecoregion of North America, have demonstrated that gravel bed streams can exhibit a wide range of responses to changes in sediment supply, including changes in channel dimensions (i.e., widening, incision), bed forms (i.e., bars, pools), and streambed texture (i.e., coarsening, fining, patchiness) (i.e., Kelsey 1980, Kinerson 1990, Buffington and Montgomery 1999a, Lisle et al. 2000, Cover et al. 2008). Predicting specific channel responses to changes in sediment supply remains difficult, however, because of the complexity of feedbacks among the streambed, sediment transport processes, and sediment supply from upstream. In this study of associations between sediment supply and streambed responses in seven tributary streams in the Lagunitas Creek watershed, bed mobility parameters and patchiness were much more strongly correlated with both quantitative and qualitative estimates of sediment supply than were measures of fine sediment. For example, the reach-average Shields parameter (τ^*) was consistently lower at sites with very low, low, and medium supply (<0.10) than at sites with high sediment supply (>0.16). Similarly, sites with very low, low, and medium sediment supply had lower values of Q* and $D'_{50} - D_{50}$ than sites with high sediment supply. Differences in mobility among the very low, low, and medium categories, however, were more consistent for τ^* and $D'_{50} - D_{50}$ than for Q*. Shear stress (τ^*) and $D'_{50} - D_{50}$ (but not Q*) were also more strongly correlated with quantitative sediment supply estimates.

Bed mobility parameters were well correlated with one another (Figure 10). Lisle et al. (2000) found a similar relationship between Q* and τ^*working in six large gravel-bed streams in northern California and Colorado (Figure 10). Although bed mobility parameters at the Lisle et al. (2000) sites were also positively correlated with sediment supply, the overall range in sediment supply was much greater (0.1 – 1800 tonnes km^{-2} y^{-1}) and the highest values of $\tau^*$and Q* were lower than in this study (Figure 11, Figure 12). Differences in hydrology, background sediment supply, or channel form between the two studies may contribute to the different relationships between bed mobility parameters and sediment supply. The low sediment supply sites of Lisle et al. (2000) were from the Colorado Rockies, streams with a distinct snow-melt hydrology, while the high sediment supply sites were from Northwestern California, an area with extremely high precipitation (>2000 mm y^{-1}) and flashy hydrologic responses. Additionally, the sites sampled by Lisle et al. (2000) were much larger (bankfull widths of 12 – 101 m) and lower gradient (0.001 – 0.006) than streams in this study.

Shields stress and Q* values suggest that full bed mobility is common in streams with high sediment supply. High values of Shields stress (>0.15 at Cheda and Woodacre), well above the criteria of 0.06 for full mobility at bankfull stage (Lisle et al. 2000), suggest that streambeds at these high sediment supply sites are very mobile. These findings are corroborated by measurements of bed mobility using painted rocks at Cheda Creek (see Appendix 1); mobility of medium and large gravels (<45 mm) in multiple patches were common during sub-bankfull flow events. Thus, it seems likely that substantial bed mobility usually occurs several times each year at these sites. Surprisingly, τ^* values at low and moderate sediment supply rates were also >0.06, suggesting frequent bed mobility occurs at these sites. These elevated τ^* values could be related to the relative paucity of scouring flood flows since a storm event that caused large inputs of sediment in 2006.

Previous flume studies have found that decreasing sediment supply led to the expansion of fixed, immobile patches, and a decrease in the total number of distinct patches (Nelson et al. 2009). In this study, I observed a strong positive relationship between sediment supply and the total number of patches in study reaches. This relationship should be considered with caution, however, because sites with the greatest patchiness also had substantial flow obstructions and roughness elements in the form of bends, wood, or bedrock (e.g., Cheda Creek, Woodacre Creek, Devil's Gulch, Larsen). Flow obstructions would be expected to result in greater numbers of "forced" patches through size-selective sorting. On the other hand, immobile, armored (i.e., "fixed") patches were only observed at sites with very low or low sediment supply: one expansive armored patch dominated the bed at Lower Nicasio Creek, and Upper Nicasio Creek had an immobile, armored bar on the margin of the upper part of the reach. All other patches at all sites showed evidence of recent mobilization. Thus, it seems likely that the same response to reduced sediment supply observed in flume studies (a narrowing of the zone of active sediment transport) also occurs in the Lagunitas Creek watershed, except only directly below dams or in areas with significantly reduced sediment supply.

Frequent bed mobility is likely to be more of a concern in tributaries, despite their smaller size, than in the mainstem of Lagunitas Creek, where sediment supply is significantly reduced by upstream dams. Kinerson (1990) calculated q* values of 0 at two locations downstream of Shafter dam (but upstream of San Geronimo Creek), and a q* value of 0.35 just downstream of San Geronimo Creek (where recent sediment supply is believed to be ~74 tonnes km^2 y^{-1} (Stillwater Sciences 2010)) (Figure 12). O'Connor and Rosser (2006), using a modified q* protocol that measured local sediment size and bankfull depth at McNeil sampling locations, found that q* values in the mainstem of Lagunitas Creek were <0.20 at most sites. Although the majority of salmonid spawning usually takes place in the mainstem of Lagunitas Creek, frequent bed mobility in tributaries could have significant effects on survival of early life stages of salmonids.

Measures of fine sediment, especially the proportion of the streambed covered by sand and/or fine gravel patches, were strongly associated with sinuosity, an important measure of hydraulic roughness in the study streams. Straight reaches had relatively small patches of fine sediment, while sinuous streams had large areas of well sorted fine sediment. This association supports the field observation that sand deposition in Lagunitas Creek tributaries is commonly associated with flow obstructions such as bends, bedrock, or wood. Although fine sediment can be very detrimental to habitats for salmonids, the results of this study suggest that flow obstructions and roughness can have a greater influence on fine sediment levels at the scale of short study reaches than upstream sediment supply. Thus, fine sediment metrics may not be as useful to monitor upstream sediment sources unless there is a way to account for local hydraulic conditions.

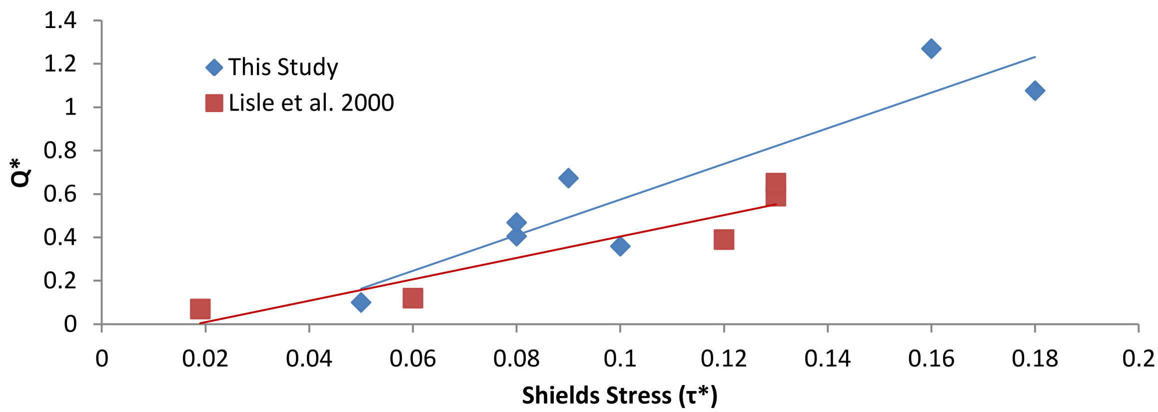

Figure 10. Relationship between Q* and Shields stress, τ*, among sites in this study and sites of Lisle et al. 2000 (values computed from reach mean hydraulic variables).

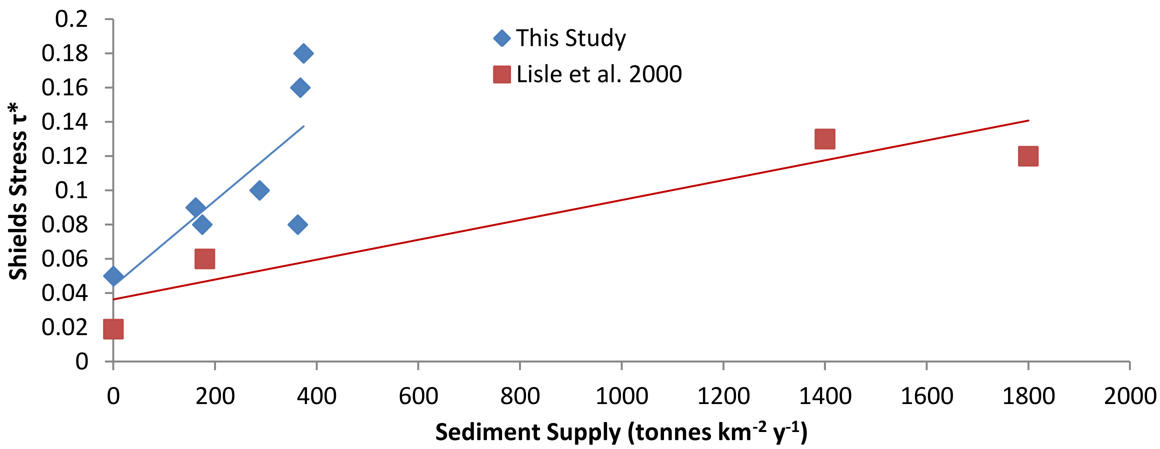

Figure 11. Relationship between Shields stress, τ*, and sediment supply among sites in this study and sites of Lisle et al. 2000 (values computed from reach mean hydraulic variables).

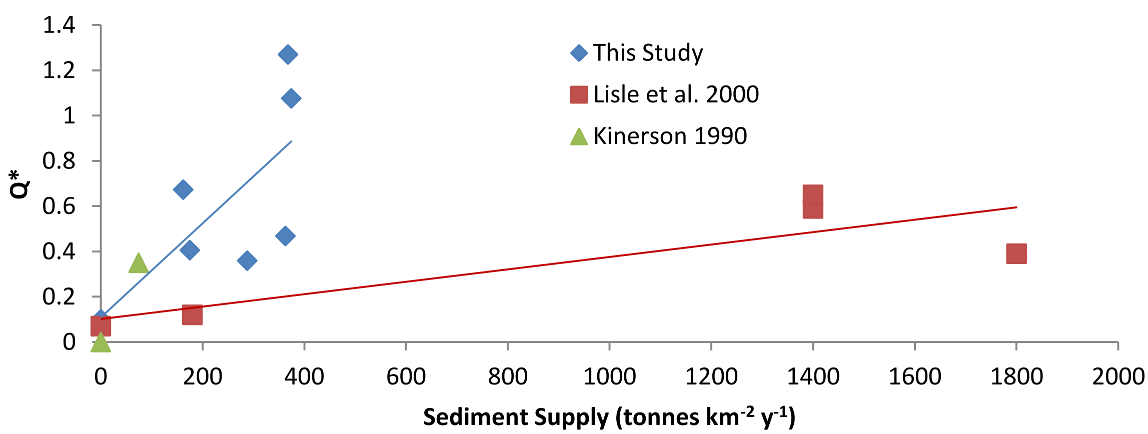

Figure 12. Relationship between Q* and sediment supply among sites in this study, sites of Lisle et al. 2000 (values computed from reach mean hydraulic variables), and Kinerson 1990 (Lagunitas Creek upstream and downstream of the San Geronimo Creek confluence).

Historical context of present-day sediment supply

Although several study streams had much lower sediment supply (i.e., Larsen and Upper Nicasio, ~160-170 t km^2 y^{-1}) than others (>350 t km^2 y^{-1}) as a result of upstream dams or debris basins, it is likely that sediment supply at "low" sites is nonetheless elevated relative to pre-disturbance levels. Natural background (<1850) sediment delivery rates in nearby watersheds have been estimated at ~50-100 t km^2 y^{-1} (Lehre 1982, Stillwater Sciences 2004), well below estimated values for present-day conditions in the Lagunitas Creek basin (except directly below dams). Following this line of reasoning, the inferred high frequency of bed mobility (high τ^* values) at "low" and "medium" sediment supply sites may also be elevated over pre-disturbance conditions, and thus may represent environmental conditions outside of the range that local populations of aquatic biota have evolved in response to over millennia.

Does it make sense that tributary streams in the Lagunitas Creek watershed are responding to elevated sediment supply through localized textural fining and increased mobility, rather than changes in slope, bed forms, or cross-sectional morphology? Historic responses to changes in hydrology and sediment supply, combined with historic management practices such as wood removal and channelization, have likely had profound effects on the present day function of these stream channels. It seems likely that all of the streams included in this study experienced significant periods of channel incision during the recent historical period (past ~200 years). Several streams (Larsen, Woodacre) are located in the naturally aggradational setting of the San Geronimo Valley, but have incised 2-3 meters below the valley floor. The other study streams also show signs of recent incision, often down to bedrock, that is likely related to early land use changes in the watershed during the later part of the 19th century. All seven study streams are now highly entrenched and disconnected from historic floodplains. Consequently, extreme floods that would have naturally spilled out onto floodplains (even if limited in extent) are now confined between steep banks, increasing basal shear stress and hence erosive power. Without increased recruitment of large wood to help store sediment, channel aggradation may not be possible in these tributary streams, even though sediment supply is elevated over pre-disturbance levels.

Potential error in bed mobility calculations

Although bed mobility parameters were strongly correlated with sediment supply in this study, and may have potential for future monitoring of sediment conditions in the Lagunitas Creek watershed, there are many potential sources of error in determining bed mobility parameters that should be carefully considered when developing monitoring protocols. For example, all three parameters (Q^*, τ^*, $D'_{50} - D_{50}$) require accurate determination of bankfull shear stress, which requires careful determination of bankfull slope and water depth. Flow obstructions, such as bends, wood, and bed topography, can cause substantial local variation in shear stress (Lisle et al. 2000) and bed surface grain size (Buffington and Montgomery 1999c). Additional sources of error exist when trying to determine bed surface grain size, which is also required for all three parameters, and subsurface grain size (required for Q^*), which is itself a proxy for the median size of bedload transport. The magnitude of these errors are rarely known unless repeat sampling is conducted. In order to examine how sources of error can affect bed mobility calculations, I performed a sensitivity analysis by recalculating bed mobility values for the seven study sites while systematically varying one input parameter (surface D_{50}, subsurface D_{50}, slope, or bankfull depth) at a time.

Errors in any of the four input parameters can have a very large influence on calculated Q* values, depending upon site specific conditions. An error of ± 5 mm in measuring surface D_{50}, for example, could result in errors in Q* of as much as -0.2 to 0.3 (Figure 13), while errors of ± 5 mm in sub-surface D_{50} produced errors in Q* as great as -0.25 to 0.5 (Figure 14). At a subset of sites, however, errors of ± 5 mm in surface and subsurface grain sizes resulted in negligible changes in Q* (i.e., <0.05); sites with small errors had coarser beds and larger differences between surface and subsurface grain sizes. Errors in slope and bankfull depth produced varied responses in Q*, depending upon whether streambeds were armored or not. Errors in slope of ±0.0025 (one quarter of one percent) resulted in Q* errors of up to ±0.3, although most sites had errors <|0.15| (Figure 15). Errors in bankfull depth of ±0.1 m generally produced errors in Q* less than ±0.2, although underestimation of bankfull depth at produced fairly large errors at a subset of sites (Figure 16).

In sum, the sensitivity analysis of Q* calculations indicates that the four input parameters must be determined with high accuracy in order to avoid substantial errors in Q* values. Although not presented here, errors in input parameters for τ*and $D'_{50} - D_{50}$ also produced extremely large errors. In order to insure that Q* values err by <0.3 (an error that would result in misclassification of sites in this study into low, medium, and high categories), errors in surface and subsurface D50 must be <5-7mm, errors in slope must be <0.002, and errors in bankfull depth must be <0.1 m. If errors are compounded, errors in individual input parameters must be even smaller.

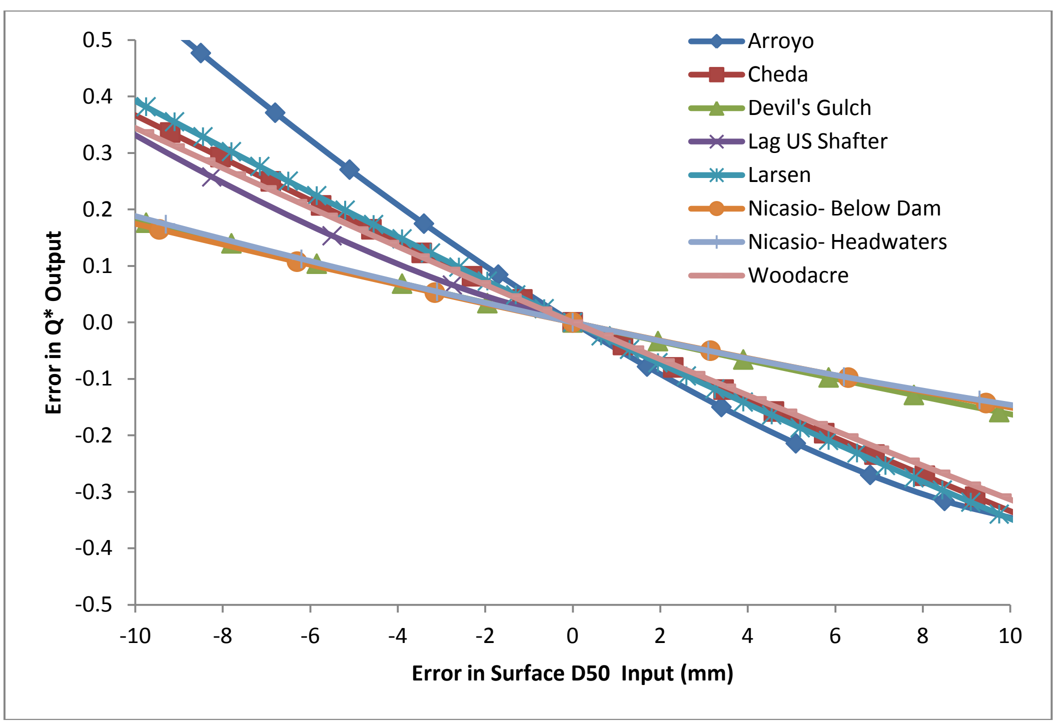

Figure 13. Sensitivity of Q* calculations to errors in surface median grain size.

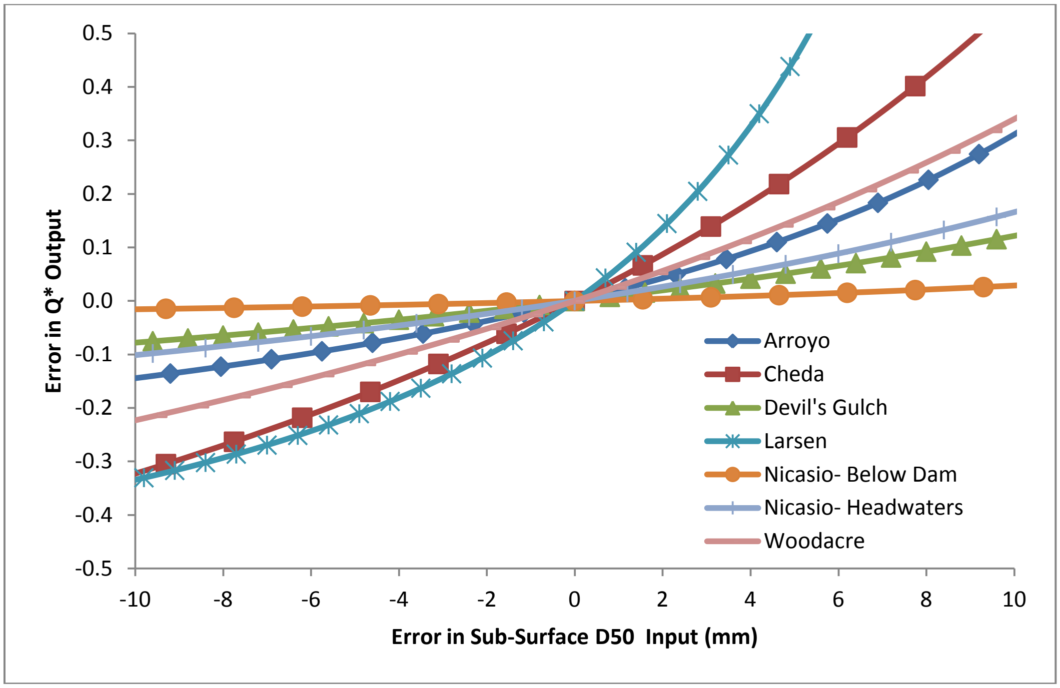

Figure 14. Sensitivity of Q* calculations to errors in sub-surface median grain size.

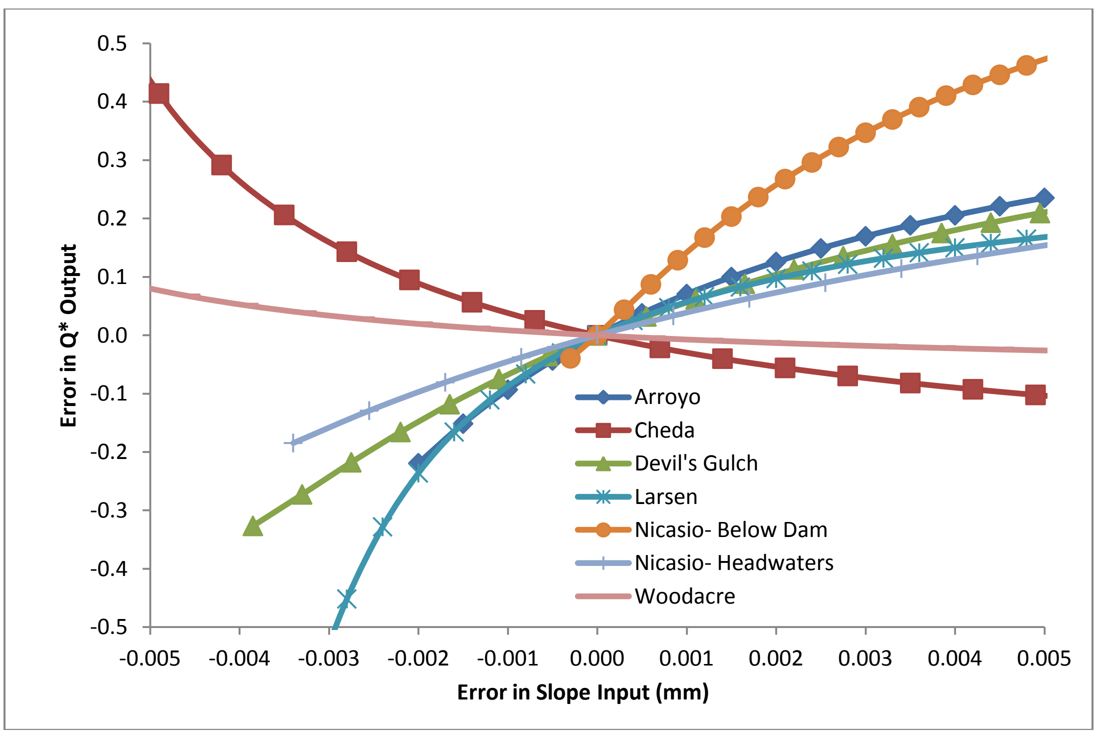

Figure 15. Sensitivity of Q* calculations to errors in slope.

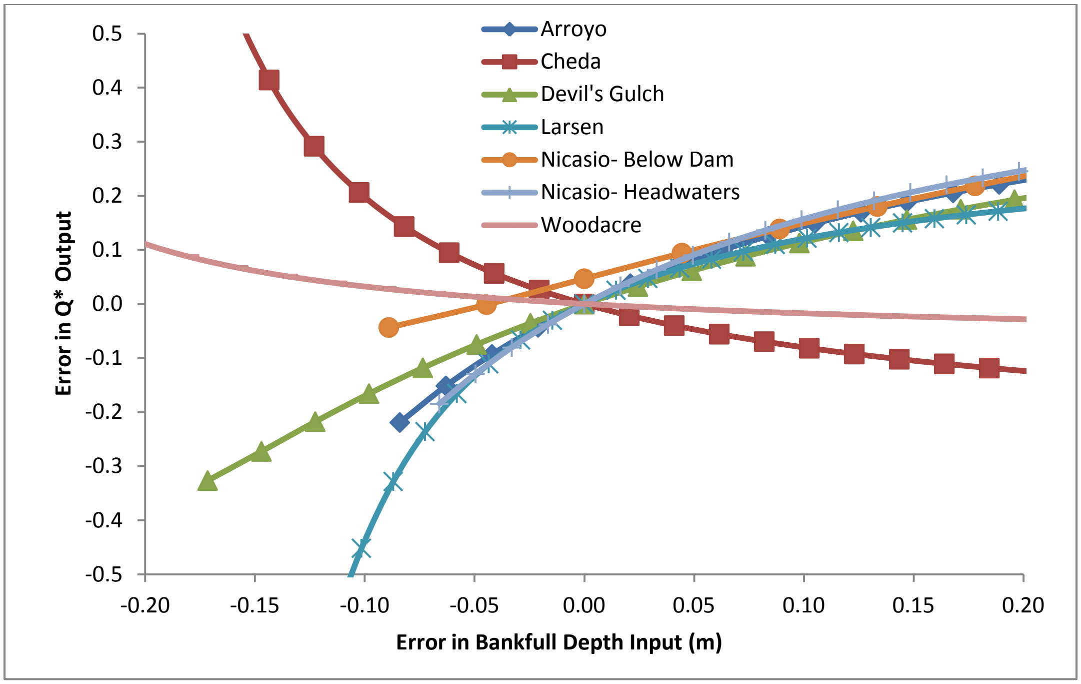

Figure 16. Sensitivity of Q* calculations to errors in bankfull depth.

Recommendations for future monitoring

Watershed monitoring programs that are focused on salmonid habitat often measure sediment-related variables such as the median grain size (D_{50}), the amount of fine sediment in the surface of subsurface, or characteristics of streambed features such as pool depth or riffle frequency. While these parameters play very important roles in structuring salmonid habitat, they are not necessarily correlated with sediment supply and are very strongly affected by local factors such as channel form and flow obstructions. Observed spatial differences or temporal changes in substrate parameters such as D_{50} could indicate changes in sediment supply, but may also reflect local changes or differences in hydraulics. Additionally, bed surface textures are often spatially organized into distinct patches. These patches may or may not overlap with distinct habitat units such as riffles or pools. Reach-averaged changes in bed surface grain size (D_{50} or fine sediment) do not convey information on whether changes are due to a coarsening or fining of the entire bed, portions of the bed, or the proportion of different patch types.

In this study I investigated the relationships among streambed characteristics (textural patches, bed mobility, and fine sediment) and sediment supply in small, tributary streams. While fine sediment parameters were poorly correlated with sediment supply, bed mobility parameters and patchiness were strongly correlated with sediment supply. There are several reasons why patch dynamics and bed mobility parameters may be a preferred approach for future monitoring of geomorphic conditions in the Lagunitas Creek watershed: (1) measuring bed mobility parameters may be more accurate than direct measurements of sediment delivery to channels (with associated uncertainties in processes, volumes, and routing through drainage networks); (2) when assessed in reaches with relatively few flow obstructions, bed mobility parameters may be less susceptible to temporal, spatial, or local variability than measures of fine sediment; (3) bed textural patches and mobility parameters reflect important aspects of salmonid habitat such as the frequency and extent of bed mobility, scour depth, and refugia from flow or predators; and (4) once the initial work to construct patch maps of study reaches is completed, changes in the size or texture of existing patches can be quickly and precisely identified during repeat surveys in subsequent years, and can be easily linked to local (i.e., wood inputs) or watershed-scale (i.e., sediment supply) perturbations.

One of the major findings of this study is that bed mobility parameters suggest that mobility and transport rates may be quite high in streams with high sediment supply (especially Woodacre Creek and Cheda Creek). At Cheda Creek, painted bed patches confirmed that bed mobility was extensive during sub-bankfull events. Additional studies of bed mobility, such as bed load transport measurements, painted patches, or other tracer particles, should be undertaken to confirm that beds in the study streams are highly mobile. Linking the dynamics of bed mobility to biological responses, such as surveys of spawning redds or juvenile salmonids before and after storms, would provide an important test of the biological significance of these geomorphic findings.

The sites in this study were selected in order to represent independent responses along a gradient of sediment supply. Although most of these streams historically and currently support salmonids, the majority of spawning and rearing habitat in the Lagunitas Creek watershed occurs in the mainstem of Lagunitas Creek and the San Geronimo Creek tributary. Thus, while the results of this study suggest the tentative conclusion that tributary streams exhibit significant textural responses to sediment supply, the results cannot necessarily be extrapolated to conditions in mainstem channels that provide the most salmonid habitat. The mainstem of Lagunitas likely represents a gradient of relative sediment supply from severely supply limited just below Peters Dam to substantially transport limited in the Tocaloma reach. It is unknown to what degree the differences in streambed conditions associated with differences in sediment supply observed in this study apply to the mainstem of Lagunitas Creek. Additional surveys of bed mobility parameters, as well as repeat surveys of patch-based pebble counts, could improve our understanding of the effects of sediment supply on streambed conditions and salmonid habitat in the mainstem of Lagunitas Creek.

Finally, from the perspective of improving habitat for salmonids and other aquatic species in the Lagunitas Creek watershed, it is important to consider not only the rates of sediment delivery to streams but how the fluvial system transports and stores that sediment. Although additional research on the historical ecology of the watershed is urgently needed, it seems clear that (1) huge declines in wood loading and (2) channel incision and a lack of connectivity with historic floodplains have fundamentally altered aquatic habitat and the way that sediment moves through the channel network. Restoration projects designed to greatly increase (i.e., by an order of magnitude) wood loading in small experimental reaches, combined with extensive pre- and post-project monitoring of channel form, streambed characteristics (including patch maps), and biological responses, would provide critical information on the efficacy and feasibility of restoring sediment routing processes to a semblance of pre-disturbance conditions.

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